Is Ethanol Made from Corn Stover a Sustainable Transportation Fuel?

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Abstract

Corn stover is the residue that is left behind after corn grain harvest. We have constructed a life cycle model that describes collecting corn stover in the state of Iowa for the production and use of ethanol in a flexible fuel light duty vehicle. The model incorporates and integrates results from individual models for soil carbon dynamics, soil erosion, agronomics of stover collection and transport, and bioconversion of stover to ethanol. It is the most comprehensive assessment of the environmental, energy and economic impacts of ethanol made from corn stover published to date.

Limitations in available data forced us to focus on a scenario that assumes all farmers in the state of Iowa switch from their current cropping and tilling practices to continuous production of corn and "no till" practices. Under these conditions, which maximize the amount of collectible stover, Iowa alone could produce almost two billion gallons per year of stover-derived fuel ethanol. Soil organic matter, an important indicator of soil health, drops slightly in the early years of stover collection, but remains stable over the 90-year timeframe studied.

We find that a mile fueled by stover-derived ethanol uses 95% less petroleum than a mile fueled by gasoline. Total fossil energy use (coal, oil and natural gas) and greenhouse gas emissions (fossil CO_2, N_2O, and CH_4) are 102% and 113% lower, respectively. Air quality impacts are mixed; with emissions of CO, NO_x and SO_x increasing, while hydrocarbon ozone precursors are reduced. Finally, the model estimates significant economic flows to the rural economy for ethanol prices that are competitive in today's fuel market. More important than the specific results of this study is the demonstrated ability to bridge the gap between advocates of sustainable agriculture and sustainable energy. We see this model as a platform for future discussion and analysis of possible sustainable scenarios for the production of transportation fuels from corn stover and other agricultural residues.

To expand this work to a level of practical use for policy makers and industry, we recommend that the Iowa analysis be redone to include long term projection for soil carbon levels, evaluate stover collection impacts for the dominant crop rotation of corn and soybeans in Iowa, expand analysis to other states, expand analysis to include wheat straw, analyze scenarios in which switchgrass and other native grasses are introduced, and consider water quality impacts.

Looking at Ethanol within the Framework of Sustainable Development

The oil crises of the 1970s sparked an interest in the United States in the development of domestic and renewable energy resources that could reduce our voracious appetite for non-renewable and foreign

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energy supplies. In the meantime, other environmental and economic concerns have broadened the debate over energy to include issues such as climate change, air quality, water quality, and sound stewardship of the land. Overlying all of these questions is the constant pressure for economic development that "lifts all boats." This often awkward and conflicting collection of social concerns is captured in the growing public debate about the possibility and pathways of sustainable development.

We began our study of the sustainability of ethanol made from corn stover by taking a step back to understand what it means to be sustainable. The classic definition of sustainable development offered by the United Nations' World Commission on Environment and Development describes sustainable development as an idealized goal of meeting "the needs of the present without compromising the needs of future generations." (WCED 1987) This offers little practical help in understanding how to get there. E. O. Wilson, the noted biologist and nature conservationist, gets down to brass tacks when he speaks of an "ethic of sustainable development" driven by the need to "expand resources and improve quality of life for as many people as heedless population growth forces upon Earth, and do it with minimal prosthetic dependence." (Wilson 1992)

Wilson's focus on the Earth as a whole drives home the importance of taking a systemic or holistic view of the technology, which we capture by using life cycle assessment. "Expanding resources," in this study, is measured in terms of the technology's ability to replace the use of non-renewable resources with the use of renewable resources. To assess impacts on the Earth, we estimate environmental flows to air, water and land—a task that is also best addressed by life cycle assessment. To assess quality of life, we minimally need to consider the economic impacts of the technology, though there are clearly many other ethical elements embodied in this term. Minimizing "prosthetic dependence" means, for our purposes, minimizing overall technological risk. Capturing this overall risk in a quantifiable way is problematic (if not impossible). In this study, we show how life cycle assessment can be used as a tool for identifying the resource, environmental, economic and technological risks and benefits of ethanol from stover. This is the first step in the genuine dialogue that must come into play when we make the kinds of choices that lie at the heart of sustainable development—choices which are, as Wilson points out, ethical in nature.

Agreeing on the Scope of the Study

In the spirit of dialogue, life cycle assessment standards call for involvement of stakeholders early in the process of setting the scope of the work (ISO 1997; ISO 1998). To that end, in May of 2000, we invited a group of farmers, environmentalists, automakers, grain processors and government researchers to come together and discuss their concerns about using corn stover to make fuel ethanol and to help us establish the scope for this study.

The Metrics of Sustainability

Starting with the broad notions of sustainable development outlined by Wilson, stakeholders established a list of metrics that they felt should be used to quantify the relative sustainability of switching from gasoline to stover-derived ethanol to fuel our cars. These are summarized in Table 1. We have been able to quantify many of these metrics. Some have been addressed in very narrow terms or in very qualitative terms. The biggest omission in the study is the lack of data on water quality effects (eutrophication), which we hope to address in future studies.

Table 1: Stakeholder-Identified Metrics of Sustainability

Metric Identified by Stakeholders	Specific Measures
Energy Security	• Fossil energy savings
	• Petroleum savings
Climate Change	• CO_2
	• CH_4 as CO_2 equivalents
	• N_2O as CO_2 equivalents
Air Quality	• Hydrocarbon ozone precursors
	• Carbon monoxide
	• Nitrogen oxides
	• Sulfur oxides
Acidification	• Equivalent H^+ to the atmosphere
Land Use and Biodiversity	• Qualitative description of land use changes
Soil Sustainability	• Soil erosion
	• Soil organic matter measured as soil carbon
Community Impacts	• Economic flows to Iowa farm communities
Solid Waste	• Hazardous and non-hazardous solid waste
Eutrophication	• Not studied
Air and Water Toxics	• Not studied

The System Boundaries

Stakeholders outlined the basic system shown in Figure 1.   The stages of the life cycle for ethanol use include: 1) production and collection of stover on the farm; 2) transport of the stover from the farm to a processing facility that produces ethanol and electricity; 3) distribution of ethanol to retail fueling stations; and 4) use of the ethanol in the form of E85 (85% ethanol/15% gasoline on a volume basis) in a flexible fuel light duty passenger car. Because we want to understand the impact of switching from gasoline to ethanol, we also include all of the life cycle stages for gasoline—from extraction of crude oil in the ground (both domestically and around the world) to the use of gasoline in the same flexible fuel vehicle. The total life cycle flows from gasoline use in this system are treated as avoided flows, meaning that they are subtracted from the life cycle flows associated with ethanol use. At the same time, a portion of the life cycle flows for gasoline production are added to the ethanol life cycle system to account for the 15% (v/v) gasoline content of E85. Similarly, we account for avoided flows associated with the conventional electricity generation that is displaced by electricity exported from the stover-to-ethanol processing facility.   At the farm, we assume changes from current farming practices (discussed in more detail later). The net flows from the farm are estimated as the difference in flows associated with the modeled changes in farm practices and flows associated with current farm practices.
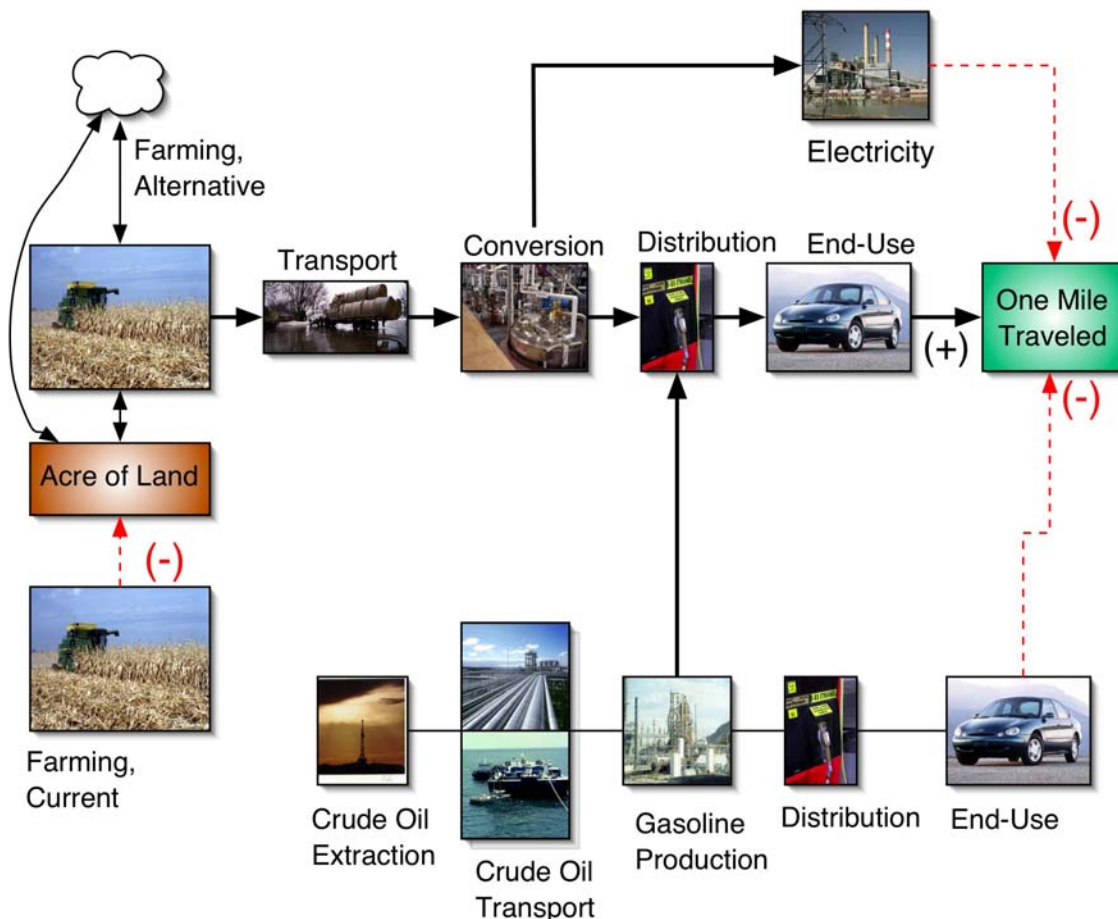
Figure 1: The Life Cycle System for Stover-to-Ethanol

The system is actually more complex than shown in Figure 1. It includes the indirect life cycle flows associated with raw materials, chemicals and fuels used in each of the stages. We exclude construction of equipment, buildings and other basic elements of infrastructure.

The Functional Basis for Measuring Changes in Sustainability

Standards for life cycle assessment require that stakeholders identify at the very start a functional unit for normalizing all of the changes in life cycle flows (ISO 1997; ISO 1998). Almost all previous life cycle studies of ethanol have reported resource and environmental flows for one mile of travel on the fuel (Delucchi 1994b; Delucchi 1994a; Riley et al. 1994; Wang et al. 1997; Wang et al. 1999). While stakeholders agreed that this was an appropriate basis for looking at stover-derived ethanol, they also suggested that we consider the changes in the sustainability of farming itself. This led to designing the system so that we could report life cycle flows of in our system for farming one acre of land as well as for traveling one mile (see Figure 1).

The Temporal Scope of the Study

Stakeholders gathered at our goal and scope meeting agreed to look at the possible impacts of a near-future (within the next five to ten years) introduction of corn stover technology. This is an important caveat. No commercial technology for ethanol production from stover exists today. The characterization of the technology is based on the best available lab and pilot scale data for technology currently under development. All other aspects of the life cycle   system are based on current practices.

Typically, life cycle assessments offer a single snapshot in time of the systems being studied. The introduction of soil carbon effects in our study requires a different approach to defining the temporal scope. The soil carbon modeling we have done is not only time-dependent, but it is specific to the initial conditions of the soil being studied. We therefore look at the effect of stover-to-ethanol technology relative to a baseline soil condition at time zero when stover collection begins (see case (b) in Figure 2 for a generic, time-dependent sustainability metric). In future studies, we hope to measure relative changes in time-dependent sustainability metrics using the difference between the new technology scenario and the time-dependent baseline, rather than using a fixed time-zero baseline (as in case (a) in Figure 2).
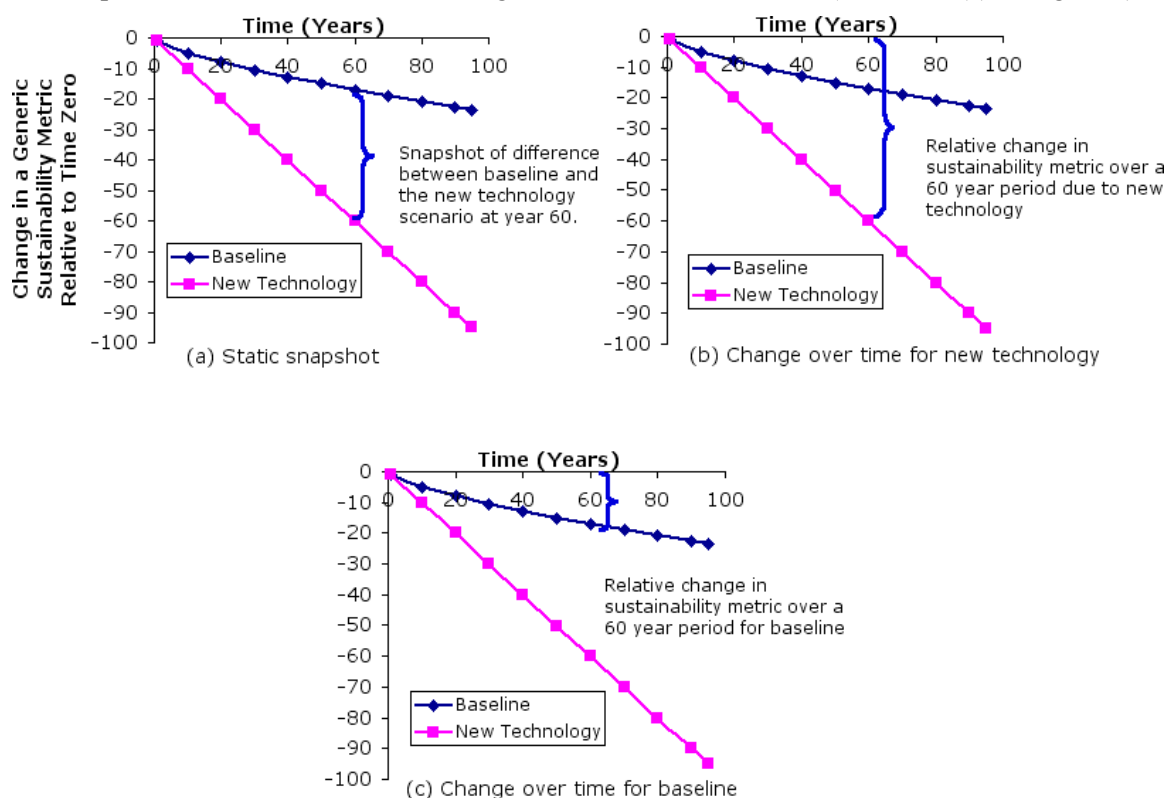

Figure 2: Different Approaches to Handling Temporal Changes in LCA Metrics (Case (b) was used in this study for soil carbon effects).

The Geographic Scope of the Study

Soil carbon and soil erosion effects are regionally specific. We use specific data for the state of Iowa to characterize stover collection and transport. Other aspects of the life cycle are not necessarily limited to Iowa. The geographic scope of the gasoline life cycle system includes worldwide oil production and Midwest gasoline production and distribution.

Modeling Tools

A comprehensive life cycle assessment requires a multi-disciplinary approach. This study brings together four highly specialized modeling tools to describe the production of ethanol from corn stover:

1. Soil erosion modeling based on USDA's Revised Universal Soil Loss Equation (RUSL) for rainfall erosion (Wischmeier et al. 1965; Renard et al. 1996) and USDA's Wind Erosion Equation (WEQ) (Skidmore et al. 1970) for wind erosion.

2. Soil carbon modeling based on Colorado State University's CENTURY model, which describes the dynamics of soil carbon flows in agro-ecosystems (Parton et al. 1988; Parton 1994; Parton et

3. Agronomic modeling for collection and transport of stover based on Oak Ridge National Laboratory's GIS-based ORIBAS model (Graham et al. 2000)

4. Process simulation for material and energy balances in the stover-to-ethanol process (Wooley et al. 1999a; Wooley et al. 1999b; Aden et al. 2002)

The results of all four models are incorporated in a life cycle model constructed using PriceWaterhouseCoopers' commercial life cycle modeling tool, TEAM™, and its companion life cycle database, DEAM™.

Modeling the Farm

Most of the cropland in Iowa is farmed in a multi-year rotation of corn and soybeans (NASS 2001). Due to limitations in data available at the start of this study, we model farming in Iowa as though all farmers instantaneously shifted from the dominant corn-soybean rotation to continuous production of corn. Furthermore, we make the assumption that all farmers switch to no till practices that maximize the rebuilding of soil carbon and the protection of soil from erosion. Thus, our results do *not* apply to farming as it is currently practiced in Iowa. Despite this limitation, the results offer useful insights about the trade-offs involved in using corn stover to make ethanol.

Constraining Residue Removal Based on Soil Erosion

Residues left behind after the grain is harvested provide surface cover that protects the soil from washing away when it rains and blowing away when it is windy. The more residues we remove, the more soil erosion we will cause. But soil erosion is also a "fact of life." It will happen with or without the "help" of farmers. So, the question we pose in this study is not whether residue collection can be done without causing erosion, but how much erosion loss we can tolerate.

We use soil erosion as a constraint on the collection of stover, rather than predicting soil erosion resulting from stover collection. In the 1970s, researchers at USDA developed a methodology for estimating how much residue could be removed and still maintain soil erosion losses within USDA's tolerable soil loss limits for various regions of the U.S. (Larson 1979; Lindstrom et al. 1979; Skidmore et al. 1979; Lindstrom et al. 1981). They accounted for climate, soil type, differences in terrain, and the total amount of residue produced, as well as the type of crops planted and the type of tilling practiced. We have adapted this methodology to estimate the maximum amount of residue that can be collected in each of the 99 counties in Iowa for continuous corn production and no till practices.

The details of our methodology are provided elsewhere (Nelson 2002). The rainfall and wind erosion models allow us to calculate the minimum residue required to be left on the field to keep the erosion within USDA tolerable loss limits. The total amount of residue produced, for corn, is calculated assuming a 1:1 ratio of residue to grain, using average corn yields reported for each county in Iowa in 1998. The difference between total residue produced and minimum residue in the field is the maximum amount of collectible residue.

Figure 3 shows the average minimum amount of residue that must be left on Iowa cornfields for a typical tilling operation (mulch till) and for no till operation, assuming that all farmers are growing corn continuously. Statewide, 24 million metric tons of residue must be left in the field for erosion prevention for mulch till practices. This drops by a factor of two if farmers adopt no till practices. For comparison, in 1998, Iowa farmers generated approximately 40 million metric tons of residue. Thus, approximately 40% of the residue can be collected under continuous corn production and mulch till, compared with 70% under no till. Note that the percentage of collectible residue will be lower for a corn-soybean rotation because of the smaller amounts of residue produced by soybean crops.
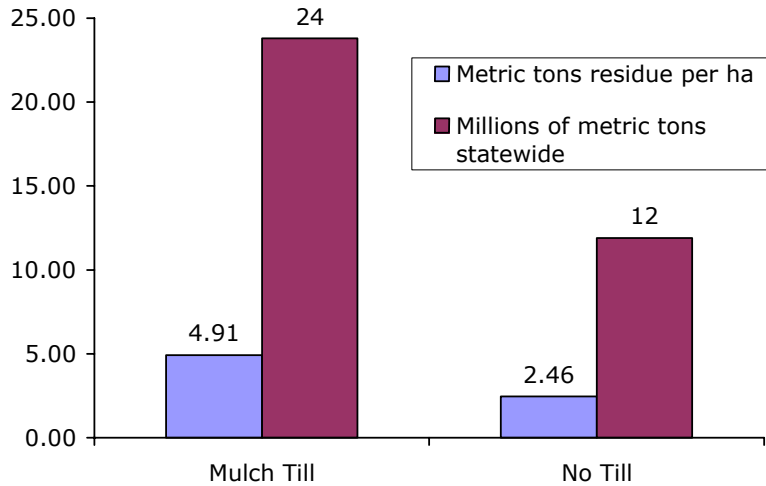
Figure 3: Minimum Residue Required in the Iowa Cornfields

Predicting Soil Carbon Levels

The choice of Iowa as the geographic scope of the farming system was driven by the availability of an extensive database of historical information on Iowa soils developed by the USDA Natural Resources Conservation Service (NRCS) in conjunction with researchers at Colorado State University (Brenner et al. 2001). This provided approximate soil carbon profiles on each county in Iowa from the mid-1800s to the present. To model the effect of switching from current practices in Iowa to continuous corn production and no till practices, we run the CENTURY model for 20 years with just the switch to continuous corn production, followed by a 95-year period in which no till practice is introduced, along with the option to remove any amount of corn stover from zero up to the maximum removable rate (as constrained by soil erosion). Soil carbon values are reported out by CENTURY at 0, 5, 10, 15, 20 and 95 years after the introduction of no till and different levels of stover removal. All other effects being equal, the soil ecosystem responds to a change in biomass carbon addition rates by asymptotically increasing or decreasing the amount of soil carbon toward a new equilibrium level (Paustian et al. 1997a), depending on whether the rate of biomass carbon addition increases or decreases.

We use a meta-model of CENTURY's predicted soil carbon response based on saturation kinetics to fit the data points reported out of CENTURY for each county to a continuous response curve. Soil carbon changes as a function of time, in the case of no stover removal, are predicted using Equation 1, a linearized form of which can be used to determine the values of a and b (Equation 2).

Equation 1: Soil Carbon Response as a Function of Time (No Stover Removal)

$$\frac{C_{s0}(t) - C_{si}}{C_{si}} = \left\lfloor \frac{t}{a + bt} \right\rfloor$$

where:

$C_{s0}(t)$ is the soil carbon level as a function of time after introduction of continuous corn production and no till operation

C_{si} is the initial concentration of soil carbon in 1995 when tillage and crop rotation changes are introduced

t is time in years

a and b are coefficients determined using a linear regression of the CENTURY data (see Equation 2)

Equation 2: Linearized Soil Carbon Response for the Case of No Stover Removal

$$\frac{C_{si}}{C_{s0}(t) - C_{si}} = a\left[\frac{1}{t}\right] + b$$

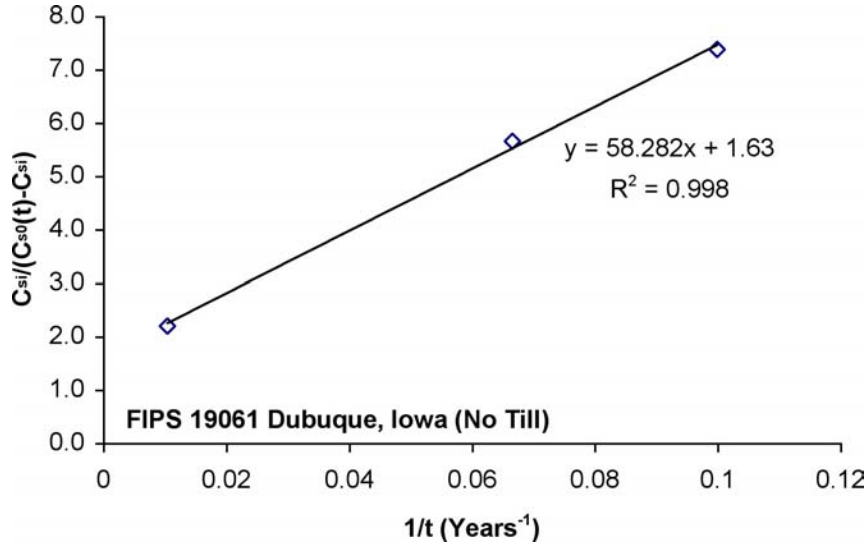Figure 4 shows the regression analysis for coefficients a and b in Dubuque County, Iowa.

Figure 4: Regression Analysis of Soil Response versus Time for No Stover Removal

An analysis of the CENTURY soil carbon results for different stover removal rates shows that the percent difference in soil carbon levels for the case of stover removal versus the case of no stover removal is linearly proportional to the fraction of stover removed at a given point in time (see Equation 3 and Figure 5).

Equation 3: Linear Response of Soil Carbon to Stover Removal at a Given Time

$$\left[\frac{C_{sr}(t) - C_{s0(t)}}{C_{s0}(t)}\right] = k(t) \times f_r$$

where:

$C_{sr}(t)$ is the amount of soil carbon at time, t, for a given removal rate of stover
$k(t)$ is a time dependent proportionality
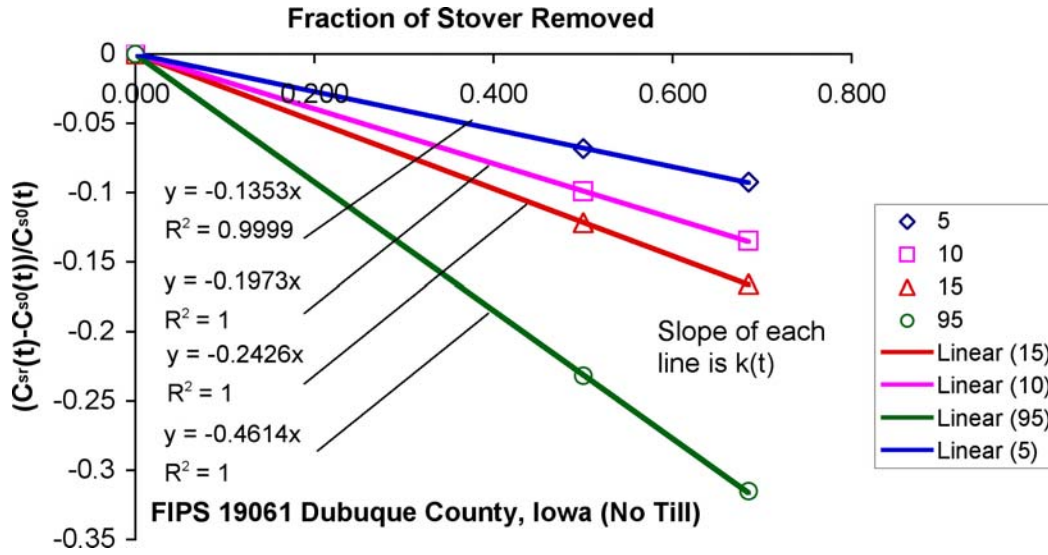f_r is the fraction of stover removed

Figure 5: Linear Response of Soil Carbon to Stover Removal for Different Times in Dubuque County, Iowa

The response of the soil to a given rate of stover removal diminishes over time as the soil approaches a new equilibrium. In our meta-model, we represent the time dependency of k as:

Equation 4: Time Dependency of k

$$k(t) = \left[\frac{t}{a_k + b_k t} \right]$$

A linearized form of this equation can be used to estimate the parameters a_k and b_k (see Figure 6).
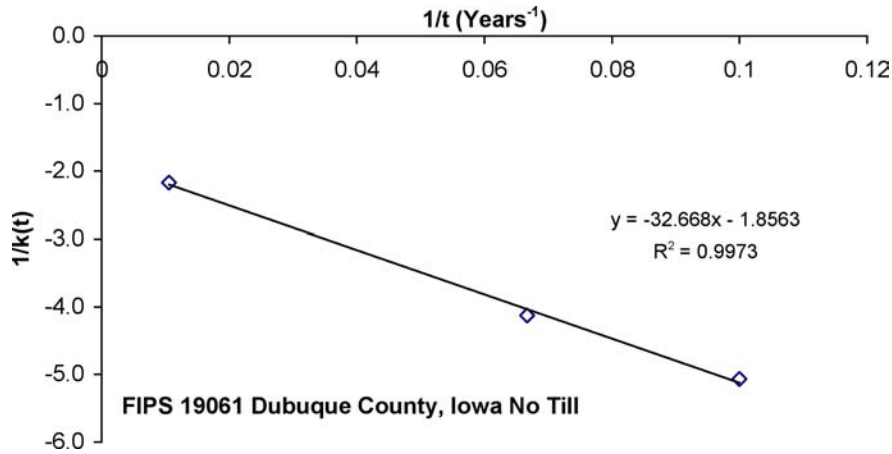

Figure 6: Regression Analysis of k(t) versus Time for Dubuque County, Iowa

Equation 1, Equation 3 and Equation 4 can be combined to solve for soil carbon level as a function of time and the rate of stover removal:

Equation 5: Soil Carbon as a Function of Time and Stover Removal Rate

$$C_{sr}(t) = C_{si}\left[1 + \frac{t}{a + bt}\right] \times \left[1 + \frac{f_r t}{a_k + b_k t}\right]$$

The soil carbon profile based on Equation 5 for Dubuque County is plotted in Figure 7 for the case of no stover removal and the case of maximum stover removal, with the actual CENTURY values shown for comparison. These results demonstrate how the switch to continuous corn production leads to a build up of soil organic matter. This benefit practically disappears when stover is removed at its maximum (erosion limited) rate.
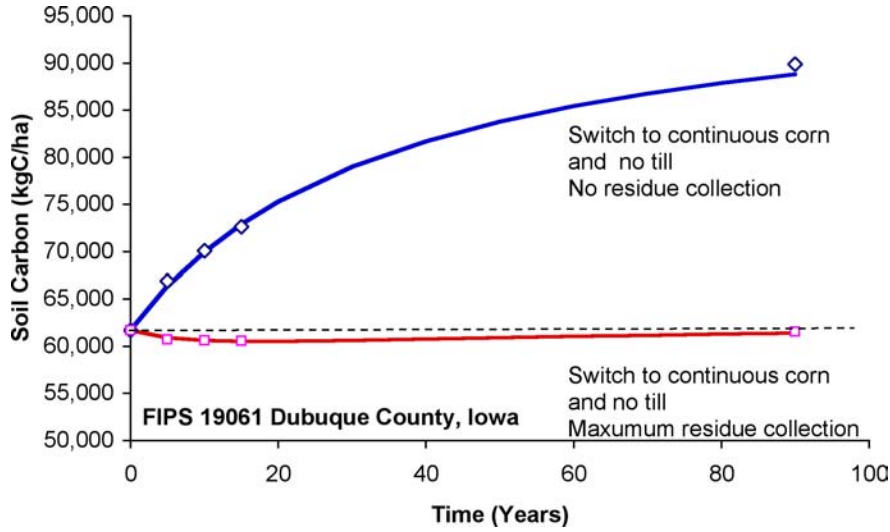

Figure 7: Soil Carbon Profiles for Dubuque County, Iowa

To calculate the emissions of carbon to or from the soil, we use the derivative with respect to time of Equation 5. The derivative was solved using Wolfram Research's CalculationCenter v1.0, and is shown in Equation 6. Carbon fluxes for Dubuque County are shown in Figure 7. The large negative fluxes associated with the scenario of no till and continuous corn production without residue collection reflects the fact that the soil is taking up carbon from the atmosphere and storing it as organic matter. Soil response equations like these are included in the life cycle model for each of the 99 counties in Iowa

Equation 6: Soil Carbon Flux as a Function Time and Stover Removal Rate

$$\frac{dC_{sr}(t)}{dt} = C_{si}\left\{\begin{array}{l}\left[1 + \left(\frac{t}{a + bt}\right)\right] \times \left[\frac{f_r}{a_k + b_k t} - \frac{f_r b_k t}{(a_k + b_k t)^2}\right] + \\ \left[1 + \left(\frac{f_r t}{a_k + b_k t}\right)\right] \times \left[\frac{1}{a + bt} - \frac{bt}{(a + bt)^2}\right]\end{array}\right\}$$
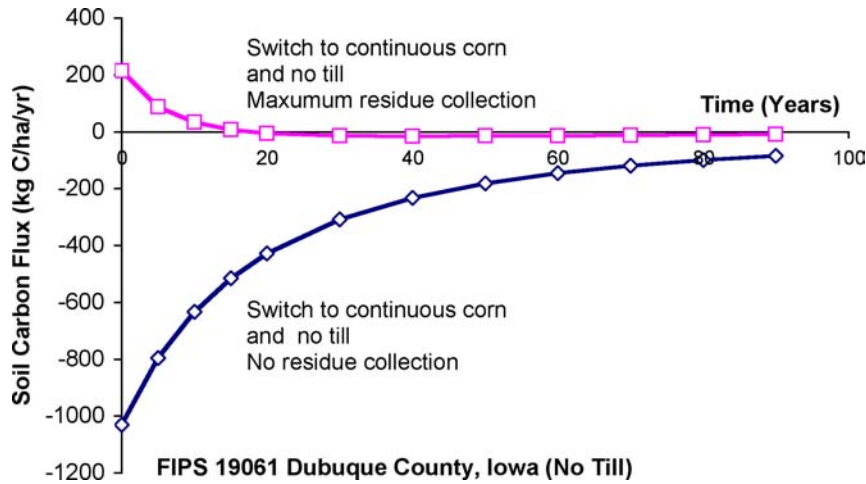
Figure 8: Soil Carbon Flux versus Time for Dubuque County, Iowa

Modeling Fertilizer Usage Changes

Switching from corn-soybean to continuous corn production causes a change in the amount of fertilizer applied. Furthermore, removal of residue from the farm results in removal of nitrogen (N), phosphorus (P) and potassium (K) contained in the residue. Most important in this change is the significant increase in nitrogen fertilizer use. Corn production has a high demand for nitrogen fertilizer, while soybean production has almost no demand at all. For nitrogen fertilizer, the incremental fertilizer demand due to the change in rotation and the make-up of nitrogen removed with the residue is:

Equation 7: Incremental Nitrogen Fertilizer Use

$$\Delta N = \frac{(1 - x_{cc})}{2}\left(N_{corn} - N_{soy}\right) + N_{residue}$$

where:

ΔN is the incremental nitrogen fertilizer burden included in the life cycle flows

x_{cc} is the current fraction of corn acres planted as continuous corn (typically around 10%)

N_{corn} is the current average rate of nitrogen fertilizer application for corn production in Iowa

N_{soy} is the current average rate of nitrogen fertilizer application for soybean production in Iowa

$N_{residue}$ is the amount of nitrogen contained in the residue removed for ethanol production

Similar calculations are done for phosphorus and potassium. Values for fertilizer use in corn and soybean production are based on USDA statistical data. Nitrogen content in the residue is based on a carbon content of 45% and an assumed C:N ratio of 100. Values for P and K content are based on chemical analyses of residue done at the National Renewable Energy Laboratory.

Modeling Soil Nitrogen Emissions

Emissions of nitrous oxide (N_2O) and nitrous oxides (NO_x) from the soil can be significant. We use guidelines from the International Panel on Climate Change (IPCC) to estimate soil nitrogen emissions associated with the switch from the current mix of continuous corn and corn-soybean rotations in Iowa to just continuous corn production (IPCC 1996). As with the estimates of fertilizer burden, we only apportion the incremental nitrogen emissions associated with the new crop management strategy.

Equation 8 shows the incremental N_2O calculation. A similar equation is used for NO_x emissions.

Equation 8: Incremental Emissions of N_2O

$$\Delta N_2O = (1 - x_{cc}) \left| \frac{N_2O_{corn} - N_2O_{soy}}{2} \right|$$

where:

ΔN_2O is the incremental amount of soil N_2O emissions

N_2O_{corn} is the emissions of N_2O for corn production

N_2O_{soy} is the emissions of N_2O for soybean production

Details of how the IPCC methodology is used are available elsewhere (Sheehan et al. 2002).

Modeling Stover Collection

A number of researchers have proposed single-pass systems in which both the corn grain and the stover could be collected simultaneously (Sokhansanj et al. 2002). Allowing farmers to collect stover and grain in a single pass through the field dramatically reduces fuel and labor costs. However, the equipment required to do this does not exist today. In this study, we model corn stover collection based on actual experience collecting stover for energy production in a second pass through the field using available commercial equipment, once the farmer has harvested the corn grain (Richey et al. 1982; Glassner et al. 1998). This is far from an optimal approach to collecting corn stover, but it reflects what we know can be done today, and it serves as a conservative starting point for looking at the life cycle impacts of using ethanol made from corn stover.

We estimate the total cost and fuel and oil use associated with the operation of harvesting equipment for stover collection cost using the methods described in the American Society of Agricultural Engineers Standards (ASAE 1998). We assume that stover is collected in 5'x6' round bales, and staged at the edge of the field for collection. Fuel, oil and cost for a range of collection rates are represented by best-fit curves such as the one shown in Figure 9 for fuel use as a function stover removal rate.
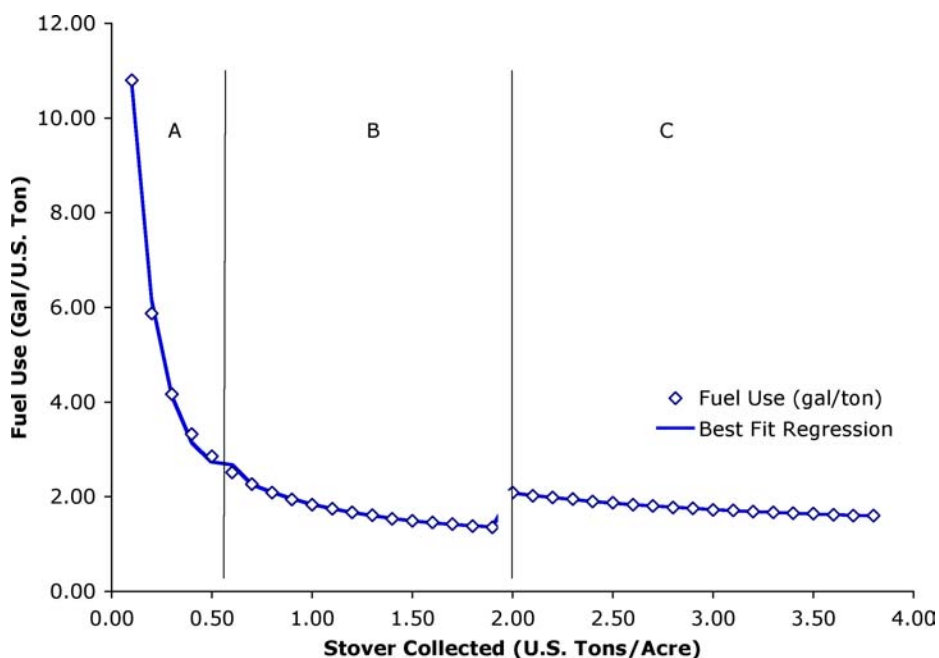
Figure 9: Fuel Use as a Function of Stover Collection Rate

The three segments of the curve labeled as A, B and C represent three different regression equations. The discontinuity in the curves between B and C reflect changes in equipment and operation assumed for stover collection rates greater than two U.S. tons per acre.

Modeling Transport

We assume that baled corn stover is delivered to an ethanol conversion facility at a rate of 2,000 tons per day on 17 bale-wagons pulled by tractors, capable of traveling up to 40 miles per hour. Bales are loaded from the edge-of-field stack using a tractor equipped with a forklift. We use our county level information on stover collection and farm level impacts as input to the ORIBAS GIS (geographic information system) based transportation model to site individual 2,000 metric ton per day (2,205 ton per day) ethanol plants across the state of Iowa (see Figure 10). The sequence of plants cited in the state is based on the location of the lowest cost stover supplies. As each new facility is added, the combined cost of collection and transport increases.
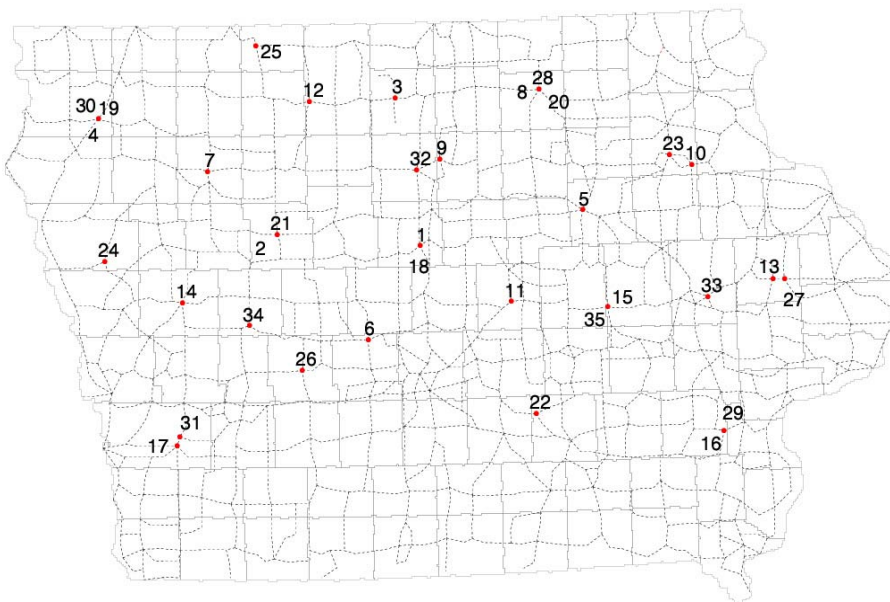

Figure 10: Citing of 2,000 ton per day Ethanol Plants Across Iowa

Modeling of the Ethanol Conversion Facility

The key to converting corn stover to ethanol is the ability to efficiently release and then ferment all of the sugars contained in the hemicellulose and cellulose fractions of the biomass. Figure 11 and Figure 12 show the overall carbon and energy flows, respectively, in the facility. Our design includes a baled stover handling section that provides milled stover to a dilute acid pretreatment and conditioning step that releases hemicellulosic sugars from the stover. Conditioning refers to a step following pretreatment in which some unwanted byproducts are removed. Pretreatment and conditioning also prepare the biomass for enzymatic hydrolysis and fermentation. In addition, the process design includes accommodations for ethanol recovery, wastewater treatment, lignin combustion for steam and electricity generation, product storage, and other utilities. The life cycle model also includes a separate facility that uses a fraction of the total stover collected in Iowa to produce the enzymes needed to break down cellulose to glucose.

Modeling Fuel Distribution and Use

Fuel distribution in the model includes the transport of ethanol by rail from the plant gate to bulk storage

terminals over an average distance of 150 miles. Blended E85 is shipped from the bulk terminal to retail outlets by diesel truck over an average distance of 100 miles. Performance and emissions data for E85 is based on EPA certification data for a Ford Taurus (model year 2000).
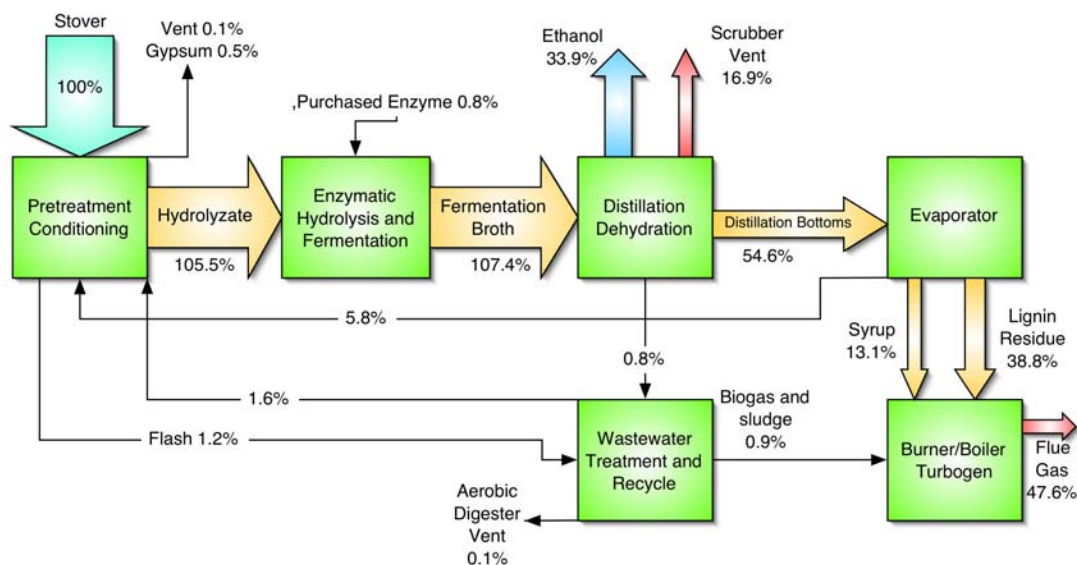
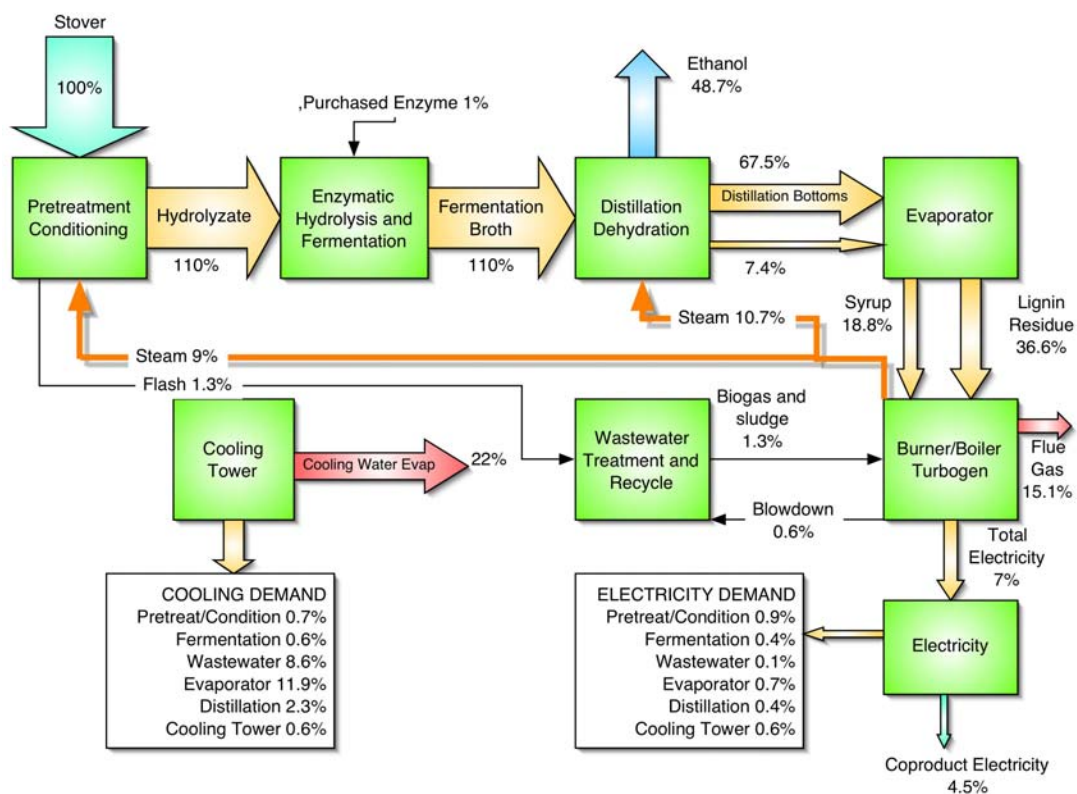**Figure 11: Overall Carbon Balance in the Stover-to-Ethanol Facility**

Figure 12: Overall Energy Balance for Stover-to-Ethanol Facility

Modeling the Gasoline Life Cycle

Modeling of the gasoline life cycle is based on updating of previously published life cycle studies comparing gasoline and diesel fuel with ethanol and biodiesel (Riley et al. 1994; Sheehan et al. 1998). It includes production and transport of both foreign and domestic crude oil. We model gasoline production and distribution for the Midwest region of the United States. Gasoline performance and emissions data are from EPA certification data for the model year 2000 Ford Taurus flexible fuel vehicle fueled with gasoline instead of E85.

Findings

We highlight results of the study for a few of the key sustainability metrics identified by our stakeholders (Table 1). As suggested by our stakeholders, we present the results of this study both from the perspective of the farm and the vehicle—that is, we look at life cycle flows normalized to an acre of land as well as normalized to one mile of travel. Furthermore, while our system is defined for a vehicle running on E85, we have set up the model so that we can vary the ethanol content in the fuel. We include results for E10 (the dominant fuel blend in today's market) and E100, as well as E85. Looking at pure ethanol as a fuel (E100) offers the advantage of being able to remove the confounding influences of gasoline in the case of E85.

Avoided flows from the gasoline life cycle, as shown in Figure 1, are subtracted from the system. Net results that are negative indicate that the avoided flows from gasoline are greater than the total flows from the production and use of ethanol.

It is important to emphasize that our results apply to a scenario for corn production in Iowa that does not exist today. It is, in fact, a scenario that maximizes stover availability and efficiency of collection.

Energy Security

We measure the long-term energy security impacts of replacing gasoline with stover-derived in terms of its effect on consumption of non-renewable energy. The gasoline life cycle consumes 5.838 MJ of non-renewable energy (results not shown here). Driving one mile on E100 reduces fossil energy consumption by 5.947 MJ (see Figure 13) —an effective savings of 102%. Decreasing the amount of ethanol in the fuel mix proportionately reduces the savings in non-renewable energy use.

To understand why the savings in non-renewable energy can be greater than 100%, we need to look at where the demands (and offsets) for fossil energy occur (see Figure 14). For E100, the farm is the greatest source of fossil energy demand. Only 16% of the energy demand in this stage of the life cycle is associated with diesel tractor operations (see Figure 15). The majority of energy demand on the farm is for fertilizer production.
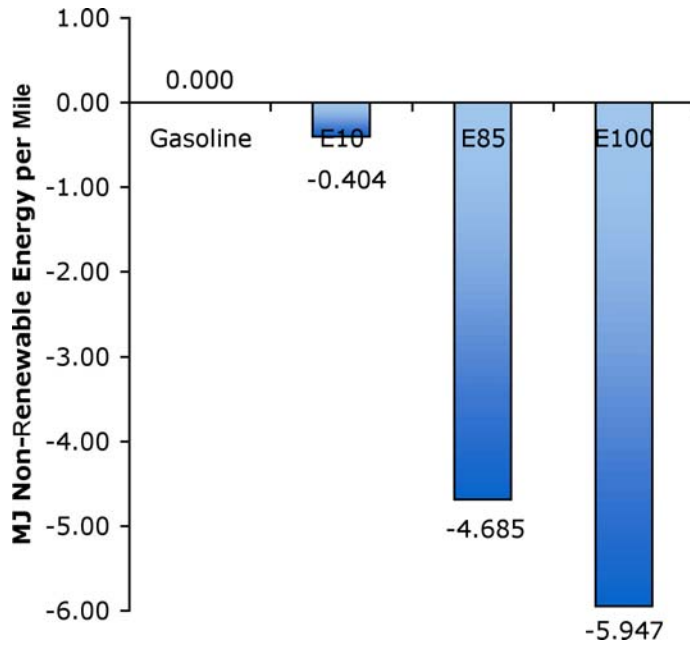
Figure 13: Net Non-Renewable Energy Use per Mile of Travel for Various Fuel Blends
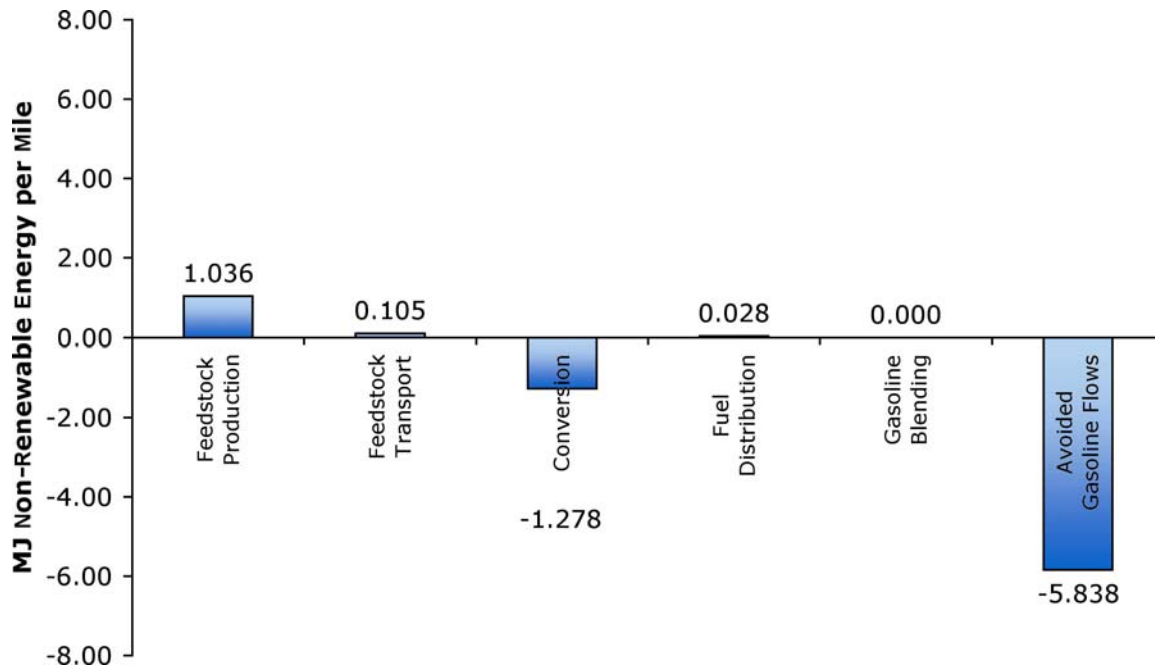

Figure 14: Sources and Offsets for Non-Renewable Energy Demand in the Ethanol Life Cycle

By comparison, the remaining fossil energy demands for transport of stover and fuel ethanol are small. These three stages represent a total non-renewable energy demand of 1.169 MJ per mile. The conversion facility provides an offset in fossil energy associated with the displacement of conventional electricity by its electricity co product. Because this offset (-1.278 MJ per mile) is larger than the total consumption of fossil energy in the other stages of the life cycle, the system has a net negative consumption of fossil energy (-0.109 MJ per mile) even before accounting for the avoided fossil energy of the gasoline life cycle.
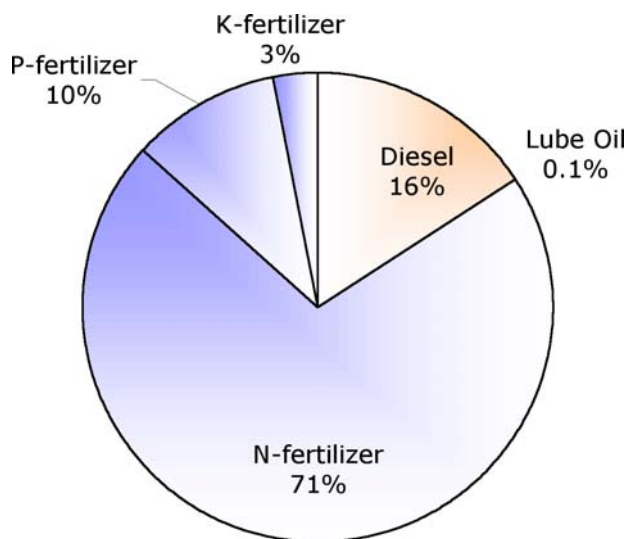
Figure 15: Sources of Fossil Energy Use on the Farm

Figure 16 compares the non-renewable energy consumption of E85-fueled travel for ethanol made from corn grain and other lignocellulosic biomass sources. These estimates include the non-renewable energy consumed to make and use the 15% v/v of gasoline in the fuel. Also, in order to be comparable to other reported energy estimates, the corn stover fossil energy estimates do not include the credit for the displacement of flows from the gasoline life cycle. Our findings for fossil savings for stover-derived ethanol are similar to the savings found in previous studies of ethanol made from other forms of lignocellulosic biomass (Wang et al. 1999) all of which are significantly better than the savings associated with today's corn grain-based fuel ethanol.
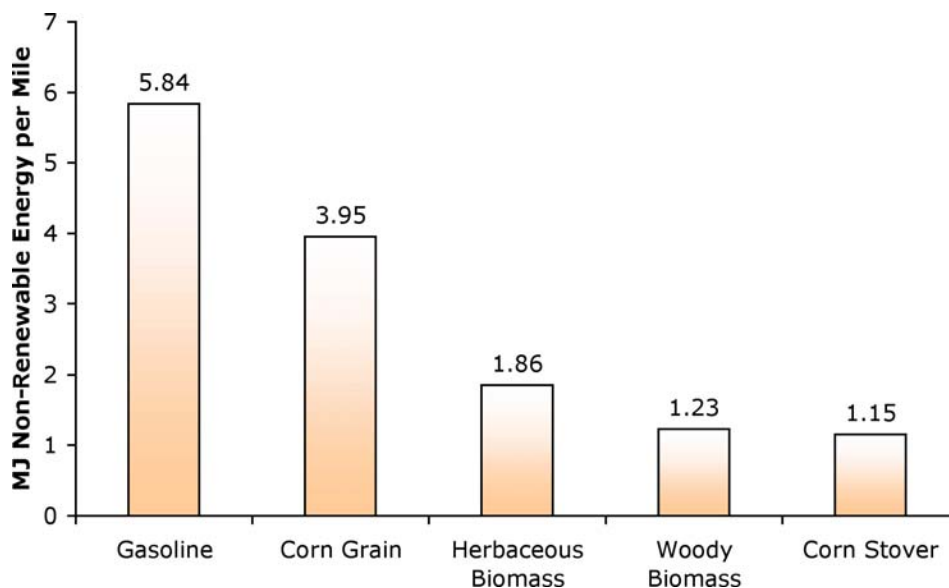

Figure 16: Comparison of Non-Renewable Energy Consumption for E85 Made from Different Feedstocks

While savings in non-renewable energy represent a long-term measure of energy security for society, savings in petroleum are the most pertinent measure of increased energy security in the near term. We estimate that stover-derived ethanol in the form of E100 reduces petroleum consumption by 95% for each

mile driven.

Looking at fossil energy resource demand from the point of view of the farm in our life cycle system offers an opportunity to see the farm in a unique light. Linking the farm to the car via ethanol production from corn stover turns the farmer into an energy supplier of some importance. As Figure 17 demonstrates, the life cycle benefits of driving on ethanol made from corn stover allow farmers to reduce our dependence on both coal and oil, though this comes at the expense of increased natural gas consumption. The net reduction in petroleum of 456 kg per acre amounts to a savings of 3.4 barrels of crude oil per acre per year for farmers who opt to participate in sustainable collection of corn stover.
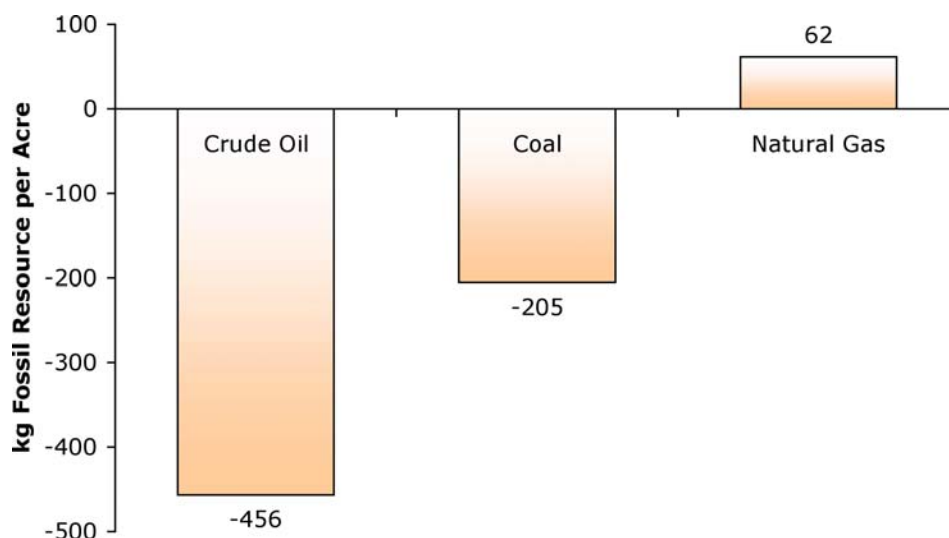

Figure 17: Net Fossil Resource Consumption per Acre of Land

Soil Sustainability

Because sustainability of the soil is inherently a land issue, we present results here that are normalized per unit of land, rather than per mile traveled. In this study, we have considered the effects of stover removal on erosion as well as on soil carbon. In the case of soil erosion, we have constrained the rates of removal to keep soil erosion rates within tolerable soil loss limits. These same constraints seem to work well for ensuring maintenance of soil organic matter as well.

Figure 18 shows a spectrum of possible aggregate (acre-weighted) statewide soil carbon profiles ranging from the extremes of maximum carbon sequestration to maximum utilization of biomass carbon for fuel production. Maximum carbon sequestration corresponds to the case of farmers' switching from their current tilling practices and crop rotations to no-till with continuous production of corn and no removal of corn stover. During the first five years at maximum stover collection, there is a small decline in soil carbon, but eventually soil carbon levels recover and even increase over the 90-year period we modeled. At "zero removal" the life cycle model predicts an increase of 32% in the level of soil carbon.

Thus, we have been able to demonstrate in this study that there are, indeed, scenarios in which corn stover can be collected while maintaining or increasing soil carbon levels. This begs the question as to whether or not the combination of no till practice and continuous production of corn represents a sustainable or sensible farm management system with respect to other important concerns, including increased pest management problems and increased fertilizer use.
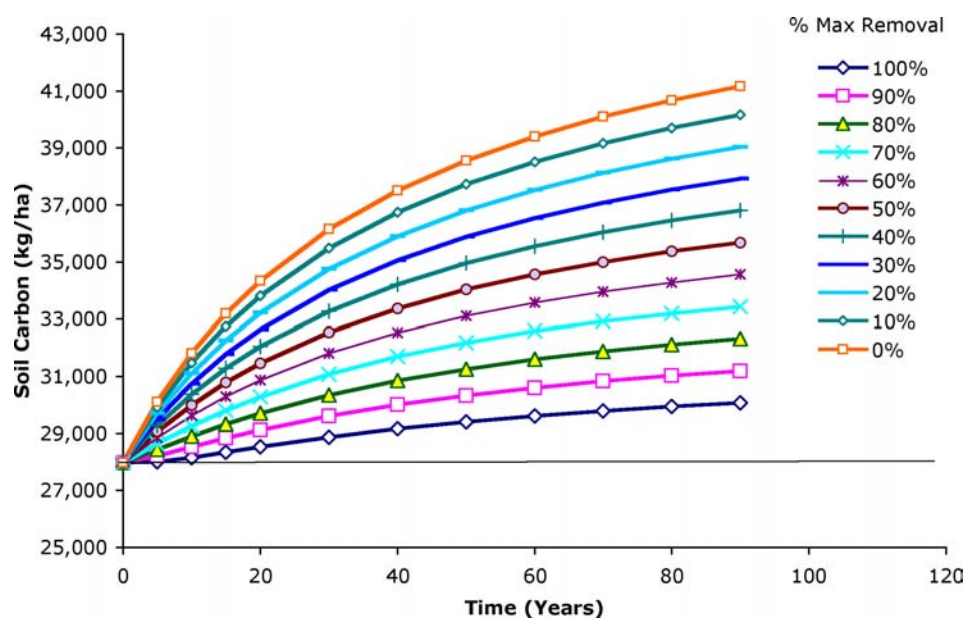
Figure 18: Statewide Soil Carbon Level versus Time for Different Stover Removal Rates (100% corresponds to the maximum stover removal rate for maintaining tolerable soil loss due to erosion)

Climate Change

Because we have introduced the dynamics of soil carbon in our model, climate change impacts estimated in this study include the year-to-year variation in the rate of exchange of CO_2 between the soil and the atmosphere. Figure 19 shows the statewide emissions of CO_2 over the 90-year period modeled in this study. There are two sources of CO_2 emissions: fossil energy use (or avoidance) and flows of CO_2 to or from the soil. Displacing gasoline with E100 reduces fossil CO_2 emissions by 429 grams of CO_2 per mile. The savings of fossil CO_2 from avoided use of gasoline amount to 379.9 grams of CO_2 per mile. In the first few years of stover collection, there is a small release of CO_2 from the soil, followed by a period of CO_2 uptake, which peaks at around 15 years, and then begins to diminish as the soil approaches a new equilibrium condition. The soil carbon effects are an order of magnitude smaller than the fossil CO_2 effects, indicating that we have chosen farm practices that minimize the effect of stover removal on soil organic matter.

In addition to CO_2, we track two other important greenhouse gases—methane (CH_4) and nitrous oxide (N_2O). The total emissions of CO_2, CH_4 and N_2O for the gasoline life cycle are 384.7 grams of CO_2 equivalent per mile. Figure 20 shows the total emissions of CO_2, CH_4 and N_2O at time zero (initial introduction of maximum stover removal), converted to an equivalent CO_2 basis, in the life cycle system for E10, E85 and E100. For each mile traveled on the ethanol fraction of the fuel (or for a mile driven on E100), total emissions of greenhouse gases drop by 409.0 grams per mile, a 106% reduction compared to gasoline.
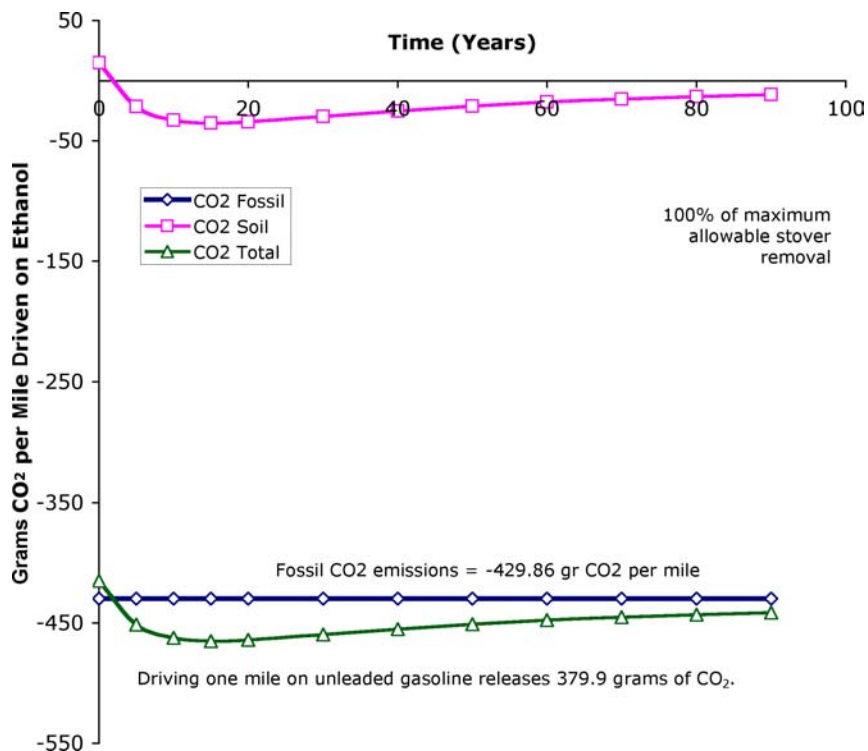
Figure 19: CO₂ Emissions per Mile versus Time
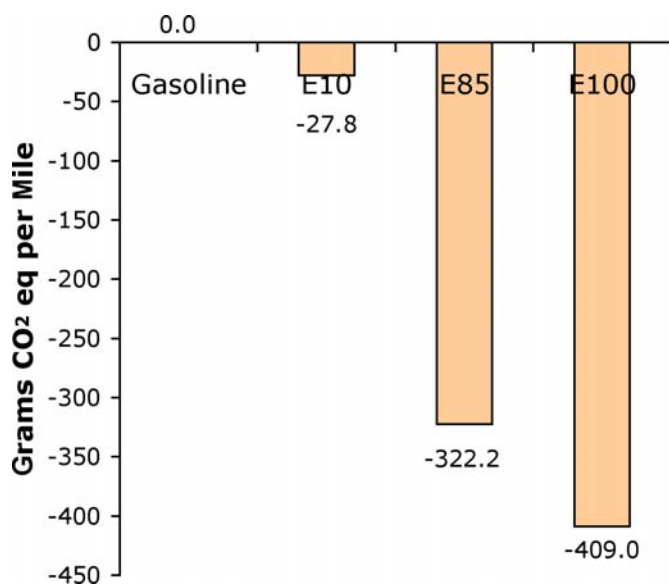
Figure 20: Total Greenhouse Gas Emissions for Various Blends of Ethanol Made from Corn Stover

Biomass carbon in stover is completed recycled in this system, and does not contribute to atmospheric greenhouse concentrations (see Figure 21). The amount of biomass carbon released as CO_2 at the conversion facility from the fermentation and lignin combustion and at the vehicle tailpipe is approximately equal to the amount of biomass carbon contained in the collected corn stover.

Figure 21: Recycling of Biomass Carbon Collected as Stover for Ethanol Production and Use

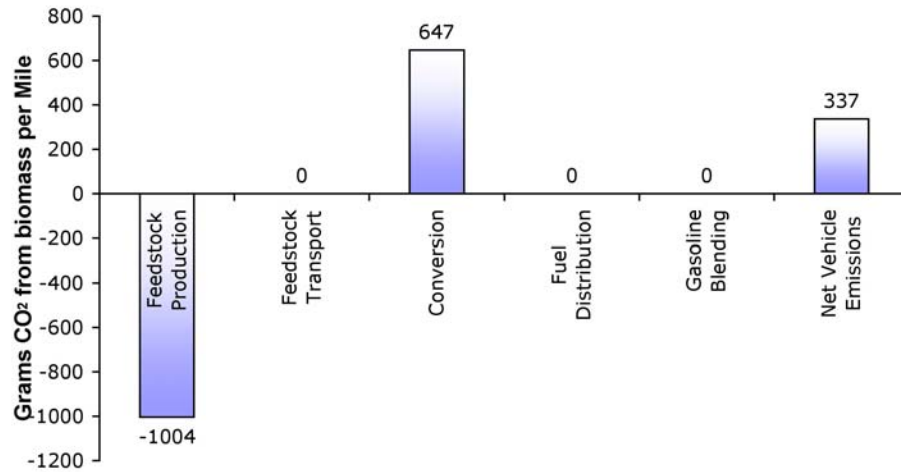The net impact on greenhouse gases comes from the avoidance of fossil CO_2 and other greenhouse gas emissions associated with the gasoline life cycle and from any direct emissions of fossil CO_2 and other greenhouse gases that occur in the ethanol production portion of the life cycle. Sources and offsets of greenhouse gases for the life cycle system at time zero are shown in Figure 22. The farm is the largest source of greenhouse gas emissions. The emissions of CO_2 from fossil use and from the initial release of soil carbon that occurs when stover collection is first introduced overshadow the emissions of methane and N_2O.

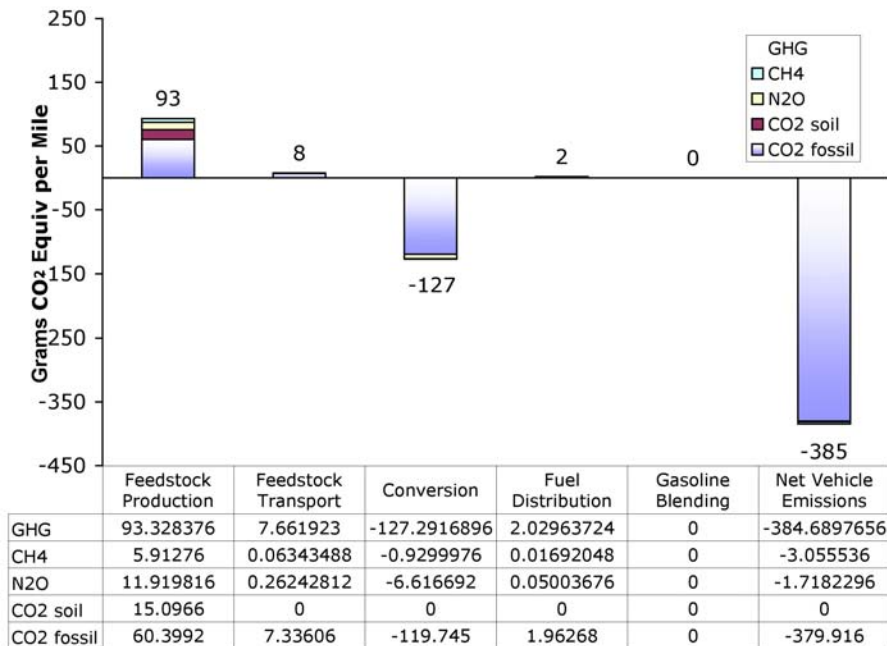|	Feedstock Production	Feedstock Transport	Conversion	Fuel Distribution	Gasoline Blending	Net Vehicle Emissions
GHG	93.328376	7.661923	-127.2916896	2.02963724	0	-384.6897656
CH4	5.91276	0.06343488	-0.9299976	0.01692048	0	-3.055536
N2O	11.919816	0.26242812	-6.616692	0.05003676	0	-1.7182296
CO2 soil	15.0966	0	0	0	0	0
CO2 fossil	60.3992	7.33606	-119.745	1.96268	0	-379.916

Figure 22: A Snapshot of the Sources and Offsets of Greenhouse Gases in the Ethanol Life Cycle taken at Time = 0 for Maximum Stover Removal

Community Impacts

We look at community impacts in terms of the economic flows generated in the rural communities of

Iowa. These flows include all direct capital and operating costs from the farm to the production of a gallon of fuel grade ethanol, all of which occurs in Iowa. We model each ethanol facility as it comes on line, making use of incrementally more expensive sources of delivered feedstock. The cumulative life cycle dollars per gallon of ethanol, including profit to the farmer and to the ethanol producer, are shown for each new 90 million gallon per year (2,000 metric ton of stover per day) facility in Figure 23. Up to about 1.87 billion gallons of ethanol capacity can be established in Iowa before costs begin to rise rapidly above $1.25 per gallon.
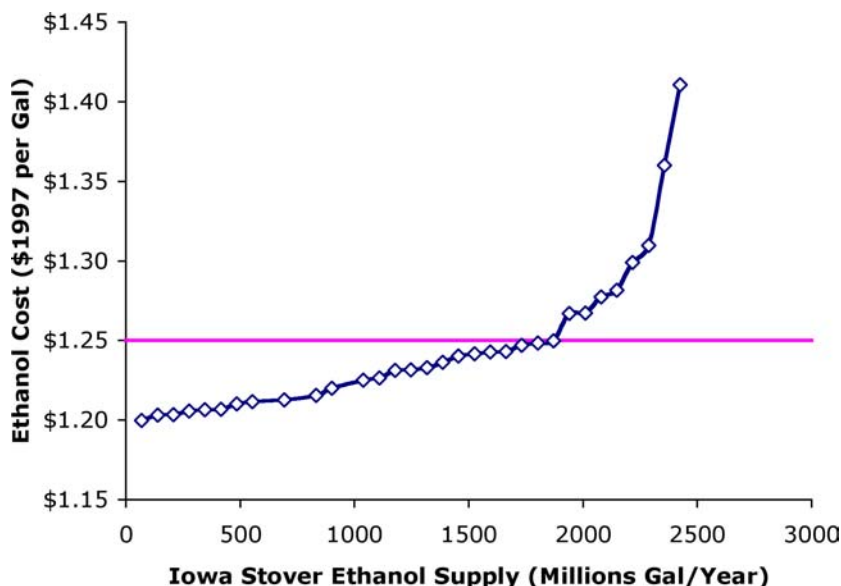

Figure 23: Cumulative Cost of Ethanol as a Function of Industry Size

We estimate, based on a combination of the total direct flow of dollars in the life cycle model and a previously published macroeconomic analysis of the impacts of a stover-to-ethanol facility built in Iowa (Walsh et al. 2000) that a fully developed 1.87 billion gallon per year industry in Iowa would add $5 billion per year to Iowa's $90 billion per year gross state product. The benefits to the farm community are very significant when we consider the fact that the total receipts in Iowa for farm commodities were $11.6 billion in 2001. Under this scenario, we estimate that this industry would generate around 35,000 new jobs.

Air Quality

Our results for air quality demonstrate the power of life cycle analysis to identify areas of potential trade-offs and areas for technology improvement. While the substitution of gasoline by ethanol causes a small decrease in the amount of ozone-forming hydrocarbons, the life cycle emissions of CO, NO_x, and SO_x are substantially higher. Nitrogen oxide emissions are almost exclusively the result of emissions from the soil on the farm. Sulfur oxide emissions are almost exclusively from the combustion of lignin residue in the ethanol facility. The dramatically higher nitrogen emissions point out the importance of applying better nutrient management practices on the farm. Sulfur oxide emissions in the ethanol facility could be corrected through better pollution controls on the boiler/burner system.
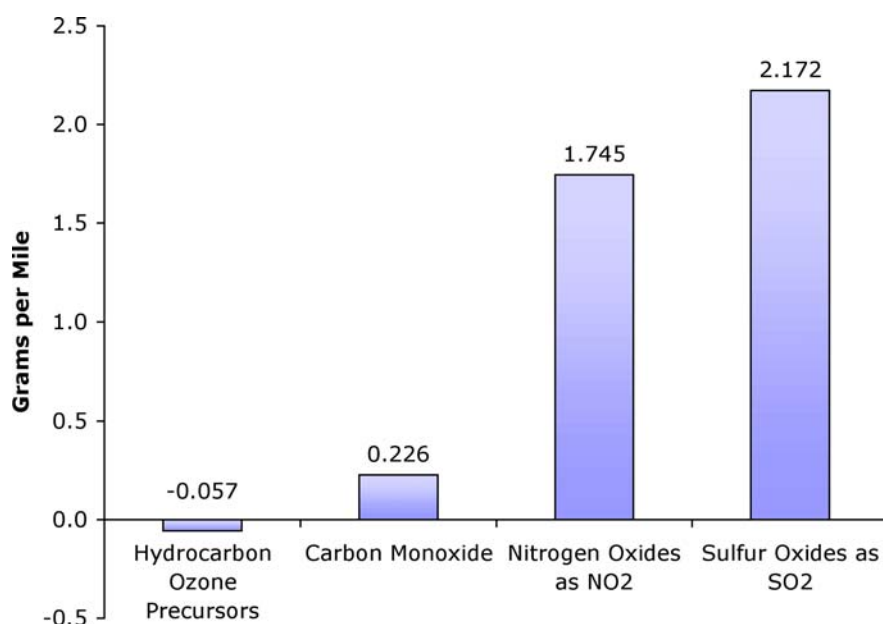
Figure 24: Air Quality Impacts of Ethanol Made from Stover (E100)

Conclusions

We have developed a life cycle model that can serve as an appropriate framework for discussing the benefits and trade-offs of substituting gasoline with ethanol made from corn stover. It is the first model that comprehensively addresses the impacts of stover collection on soil health, measured in terms of both of soil erosion and soil organic matter. These results by no means definitively answer the question of whether stover is a sustainable source of energy for transportation. Rather, we see these results as demonstrative of the kind of "what if" scenarios that can be assessed with such a model. In the current study, we have used the model to look at one possible scenario of farm practices and stover removal that can maintain soil quality, while providing for substantial production of transportation fuel. Many other aspects of the farm must be considered before we can answer the question of how to collect and use stover sustainably. Our model can provide the means for meaningful debate about the benefits and trade-offs of stover for energy.

Recommendations for Next Steps

This project represents a first step in learning how to look at soil sustainability issues for agricultural residues collection in a life cycle context. To expand this work to a level of practical use for policy makers and for industry, we need to:

1. Redo the Iowa analysis to include a long term projection for soil carbon levels and greenhouse gas emissions for the current mix of tilling and cropping practices

2. Evaluate stover collection impacts for the dominant crop rotation of corn and soybean production in Iowa

3. Expand our analysis to other states

   a. At a minimum, this analysis should be expanded to included additional states for which soil carbon inventories have now been completed by CSU-NREL (Indiana and Nebraska)

   b. Ultimately, we should expand the analysis to cover the top ten corn and wheat producing states. The bottom line of this expanded analysis is to provide a more accurate picture of the potential impact agricultural residues can have on U.S energy supplies and U.S.

greenhouse gas emissions.

4. The analysis should be expanded to include wheat straw

5. We should analyze scenarios in which switchgrass and other native grasses are introduced in the rotation cycle

6. Water quality impacts need to be considered. The problems of water impacts from agriculture are very high on the list of concerns raised by environmental organizations. The current modeling should be expanded to include leaching of nutrients from the soil into groundwater and pollution of surface waters due to water runoff.

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